Measurement of Longitudinal Spin Asymmetries for Weak Boson Production in Polarized Proton-Proton Collisions at STAR

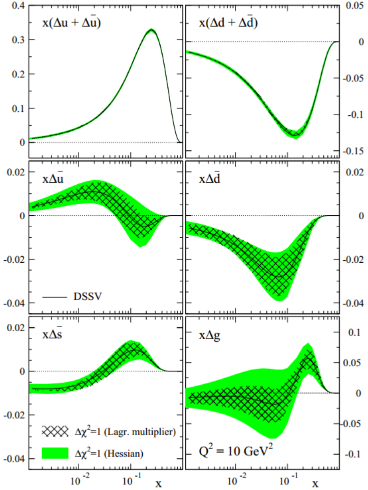
Jinlong Zhang , for the STAR Collaboration

Shandong University & Brookhaven National Laboratory

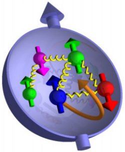
RHIC/AGS Users' Meeting
June 17th, 2014

Proton Spin Puzzle

DSSV Global Analysis

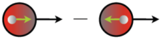


PRD 80, 034030 (2009)



Polarized PDFs:

$\Delta f(x) =$



$f^+(x) - f^-(x)$

$$< S_p > = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

(Jaffe-Manohar, 1990)

$$\Delta\Sigma = \int(\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s})dx$$

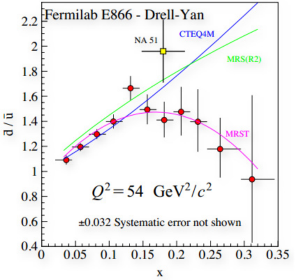
Integral of quark polarization is well measured in DIS to be $\sim 30\%$, some info on decomposition from SIDIS but sea quarks are not well constrained.

$$\Delta G = \int \Delta g(x)dx$$

First experimental evidence of non-zero Δg from 2009 data

(See Brain Page's talk)

Flavor Asymmetry of the Sea



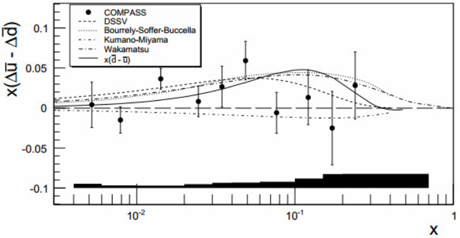
PRD 64, 052002 (2001)

Unpolarized Flavor Asymmetry:

- Quantitative calculation of Pauli blocking does not explain $\bar{d}/\bar{u}$ ratio
- Non-perturbative processes may be needed in generating the sea
- E866 results are qualitatively consistent with pion cloud models, chiral quark soliton models, instanton models, etc.

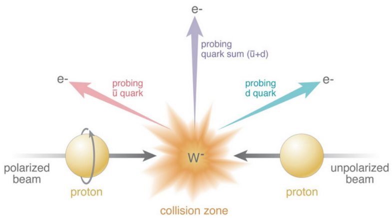
Polarized Flavor Asymmetry:

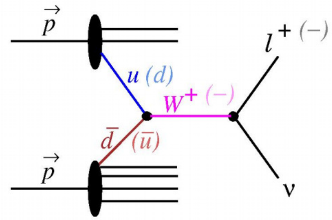
- Valence u and d distributions are well determined from DIS
- Polarized flavor asymmetry x$(\Delta\bar{u} - \Delta\bar{d})$ could help differentiate models
- SIDIS results depend on FFs



PLB 693, 227 (2010)

Why Ws ? — Unique Probe to Sea Quark Polarization





- Ws couple directly to the quarks and anti-quarks of interest
- V-A coupling of the weak interaction leads to perfect spin separation
- W charges allow flavor separation
- Detect W^+/W^- through e^+/e^- decay channels

$$u + \bar{d} \to W^+ \to e^+ + \nu$$

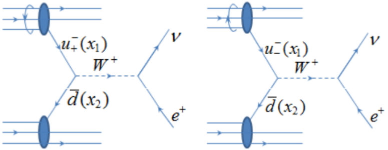
$$d + \bar{u} \to W^- \to e^- + \bar{\nu}$$

Measure parity-violating single-spin asymmetry:

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

Why Ws ? — Unique Probe to Sea Quark Polarization

A. Polarized (subscript) proton provides *u*



A.1 Proton helicity = "+" **A.2** Proton helicity = "-"

$$A_L^{W^+} \propto \frac{u_+^-(x_1)\bar{d}(x_2) - u_-^-(x_1)\bar{d}(x_2)}{u_+^-(x_1)\bar{d}(x_2) + u_-^-(x_1)\bar{d}(x_2)} = -\frac{\Delta u(x_1)}{u(x_1)}$$

* dominate forward W^+

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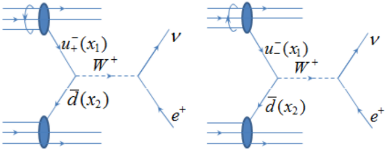

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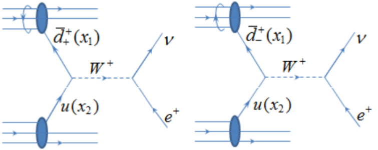
B. Polarized (subscript) proton provides $\bar{d}$



B.1 Proton helicity = "+" **B.2** Proton helicity = "-"

$$A_L^{W^+} \propto \frac{\bar{d}_+^+(x_1)u(x_2) - \bar{d}_-^+(x_1)u(x_2)}{\bar{d}_+^+(x_1)u(x_2) + \bar{d}_-^+(x_1)u(x_2)} = \frac{\Delta \bar{d}(x_1)}{\bar{d}(x_1)}$$

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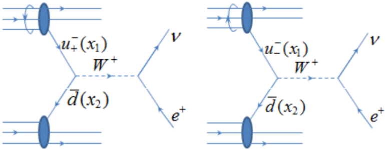

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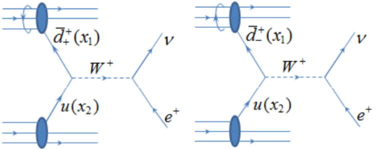

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* dominate backward W^+

Superpose **A** and **B** :

$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

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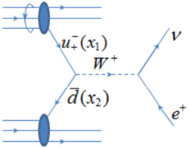

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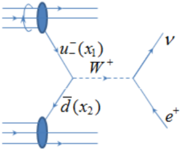

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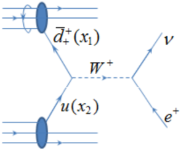

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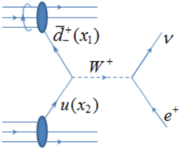

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Superpose **A** and **B** :

$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

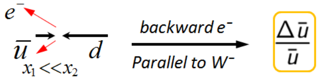
Switch u and d :

$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

Expectation for W A_L

- Large parity-violating asymmetries expected.
- Simplified interpretation at forward and backward rapidity.

$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2)+\Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2)+\bar{u}(x_1)d(x_2)}$$



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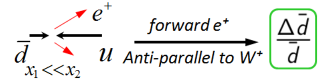
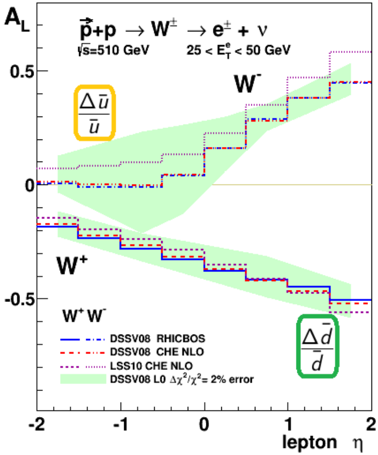
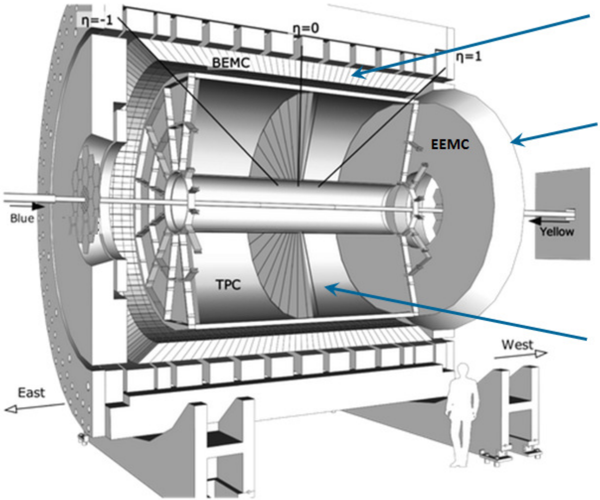




*Charged lepton tends to emitted parallel (anti-parallel) to $W^-(W^+)$ due to the handedness of produced neutrino.

STAR Detector Overview



Triggering Barrel EM Calorimeter: $|\eta|<1$

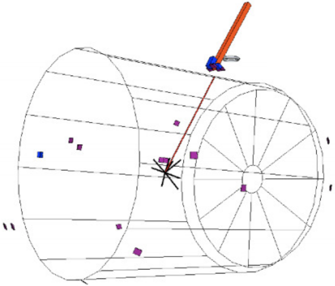
Triggering Endcap EM Calorimeter: $1.1<|\eta|<2$

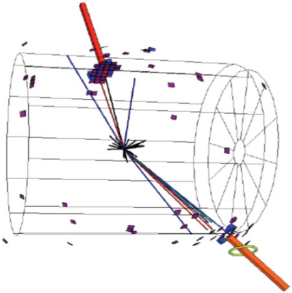
Time Projection Chamber: Charged particle tracking $|\eta|<1.3$

Sample W Candidates

$W \rightarrow e + \nu$ **Candidate Event:**

- Isolated track pointing to isolated EM cluster in calorimeter
- Large "missing energy" opposite the electron candidate

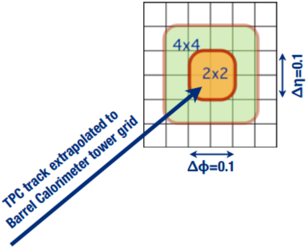




QCD Background Event:

- Several tracks pointing to EM energy deposit in several towers
- Vector p_T sum is balanced by opposite jet, no large "missing energy"

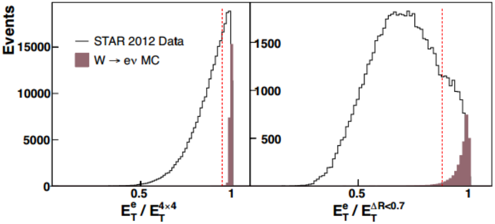
Isolation Cuts



Transverse Plane views

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

- Match $p_T > 10$ GeV track to EMC cluster
- Require the energy deposited in the next ring to be <5% of the 2x2 sum
- Require the ratio $E_T^e / E_T^{\Delta R<0.7}$ to be $> 88\%$



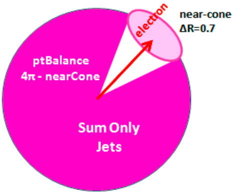
Topological Cuts

P_T-balance:

$$\vec{p_T}^{\,bal} = \vec{p_T}^{\,e} + \sum_{\Delta R > 0.7} \vec{p_T}^{\,jets}$$

$$\text{signed } P_T\text{-balance} = \frac{\vec{p_T}^{\,e} \cdot \vec{p_T}^{\,bal}}{|\vec{p_T}^{\,e}|}$$

required to be > 14GeV



Transverse Plane views

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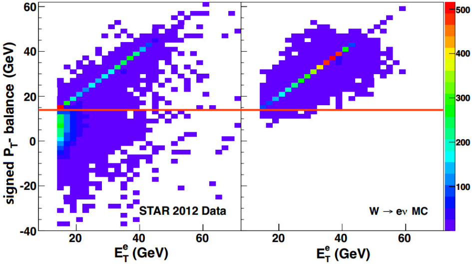
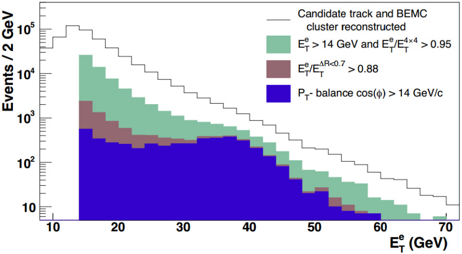
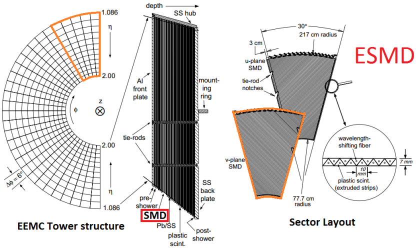


* Signed p_T-balance vs. E_T^e (data on the left and W MC embedded simulation on the right)



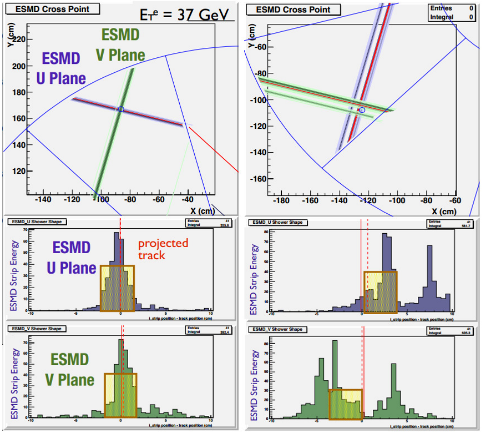
* E_T^e distribution as background cut away

- Similar isolation and topology cuts as barrel region
- Additionally improve background rejection by using the Endcap Shower Maximum Detector (ESMD)



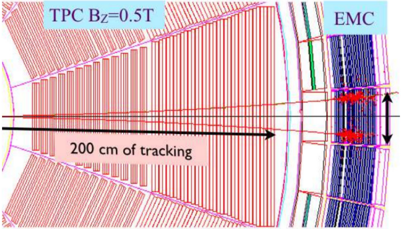
Events pass all previous cuts

Signal Example **Background Example**

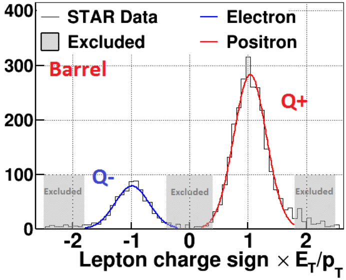


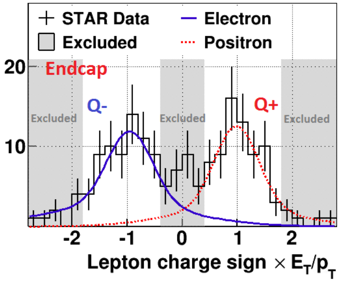
$$R_{ESMD} = \frac{\sum_{i=-3}^{3} E_i^U + E_i^V}{\sum_{i=-20}^{20} E_i^U + E_i^V} > 0.6$$

Charge Separation



distance D ~ 1/pT , pT=5GeV D~15cm, pT=40GeV D~5cm

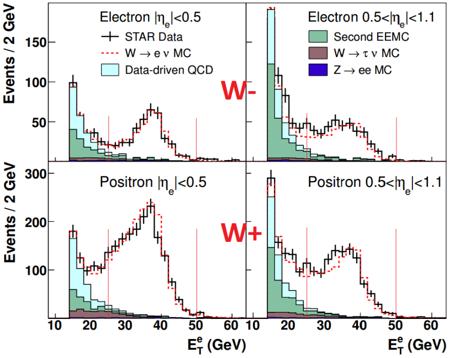




- Charge sign reconstruction based on TPC track bending
- Estimate wrong sign contamination by fitting $Q * E_T/pT$ with Gaussian.

Mid-rapidity Background Estimation

arXiv: 1404.6880



*** E_T^e distribution of W^- (top) and W^+ (bottom) candidate event of 2011+2012 data (black), background contributions , sum of backgrounds and $W^\pm \to e^\pm \nu_e$ MC signal (red-dashed)**

$$W^+\ \beta:\ \sim 0.95,\ W^-\ \beta:\ \sim 0.9$$

where $\beta = S/(S+B)$, S and B are the number of signal and background events in [25, 50] GeV

W signal

- "Jacobian Peak"

Primary Background:

Satisfy W selection cuts but contain jets escaping detection at $\eta < -1$ and $\eta > 2$.

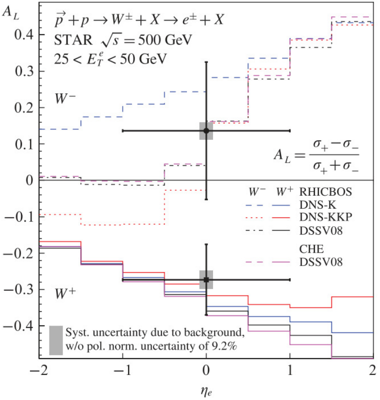
- **Second EEMC**
  Estimate non-existent "east" EEMC background based on real west EEMC
- **Data-driven QCD**

Electroweak Background:

Determined from Monte-Carlo simulation.

- **Z → ee MC**
- **W → $\tau\nu$ MC**

W Data from 2009 to 2012



PRL 106, 062002 (2011)

- 2009 was a very successful first 500 GeV physics run

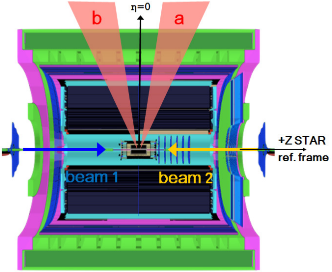
Statistics increase of an order of magnitude from 2009 to 2012:

STAR pp500 Longitudinal		
Run	L (pb^{-1})	$W^+(W^-)$ raw yield
2009	12	462 (192)
2011	9	342 (103)
2012	77	2417 (734)

With larger statistics, we can look into lepton pseudo-rapidity, η_e, dependence of spin asymmetry

Extract Spin Asymmetry with Profile Likelihood Method

- ✓ Profile Likelihood method was used in combination of 2011 and 2012
- ✓ Accommodate the low statistics of 2011 dataset



Define a likelihood function for 8 spin-dependent yields from pair of symmetric η region of STAR :

$$L = \prod_i^4 \mathcal{P}(M_i^a|\mu_i^a)\mathcal{P}(M_i^b|\mu_i^b)g(\beta^a)g(\beta^b)$$

- *$\mathcal{P}(M_i|\mu_i)$ is Poisson probability, for measured spin sorted yield M_i in the expected value μ_i given by :*

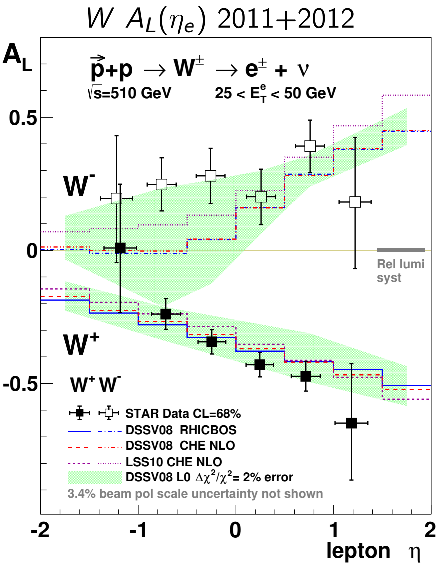
$$\begin{aligned}
\mu^a_{++} &= l_{++}N(1 + P_1\beta A_L^{+\eta_e} + P_2\beta A_L^{-\eta_e} + P_1P_2\beta A_{LL}) \\
\mu^a_{+-} &= l_{+-}N(1 + P_1\beta A_L^{+\eta_e} - P_2\beta A_L^{-\eta_e} - P_1P_2\beta A_{LL}) \\
\mu^a_{-+} &= l_{-+}N(1 - P_1\beta A_L^{+\eta_e} + P_2\beta A_L^{-\eta_e} - P_1P_2\beta A_{LL}) \\
\mu^a_{--} &= l_{--}N(1 - P_1\beta A_L^{+\eta_e} - P_2\beta A_L^{-\eta_e} + P_1P_2\beta A_{LL})
\end{aligned}$$

**where $P_1(P_2)$ beam polarization, $A_L^{+\eta_e}(A_L^{-\eta_e})$ single-spin asymmetry, A_{LL} double-spin asymmetry, N_a spin averaged yield, $l_{\pm\pm}$ the relative luminosity*

- *$g(\beta)$ is Gaussian probability for estimated dilution background, $\beta = S/(S+B)$.*

Extract asymmetries from likelihood function $L_{2011} \times L_{2012}$

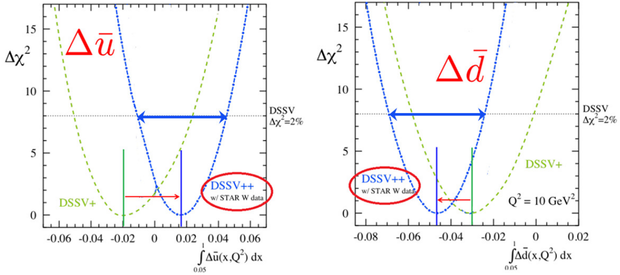
$W\ A_L$ Result of 2011+2012



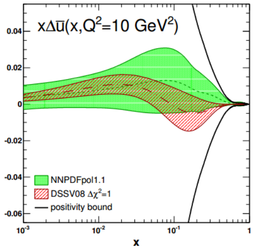
arXiv: 1404.6880

- STAR measured the parity-violating single-spin asymmetry A_L for $|\eta_e| < 1.4$ from 2011 and 2012 data
- Provide the first detailed look at the asymmetry's η_e dependence
- $A_L(W^+)$ is consistent with theoretical prediction
- $A_L(W^-)$ is larger than the predictions for $\eta_e < 0$, which is particularly sensitive to $\Delta\bar{u}$

Impact of STAR Result



DSSV++ arXiv: 1304.0079



NNPDFpol1.1 arXiv: 1403.0440

- STAR 2012 preliminary results included in global fits by **DSSV** and **NNPDF**.
- STAR run12 W results provide significant constraints on $\bar{u}$ and $\bar{d}$ polarization.
- Shift in central values for $\Delta\bar{u}$ and $\Delta\bar{d}$ after including STAR run12 preliminary results

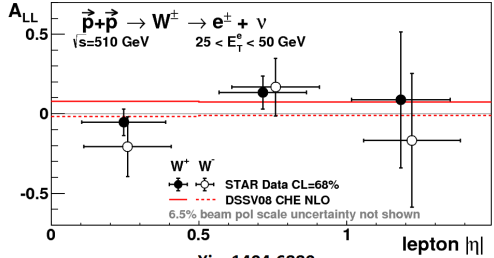
Measure double spin asymmetry:

$$A_{LL} = \frac{(\sigma^{++}+\sigma^{--})-(\sigma^{+-}+\sigma^{-+})}{(\sigma^{++}+\sigma^{--})+(\sigma^{+-}+\sigma^{-+})}$$

- Probes different combination of quark polarizations

$$A_{LL}^{W^+} \sim \frac{\Delta u}{u}\frac{\Delta \bar{d}}{\bar{d}} \qquad A_{LL}^{W^-} \sim \frac{\Delta d}{d}\frac{\Delta \bar{u}}{u}$$

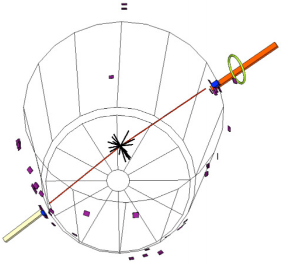
- Proposed to test positivity constraints using a combination of A_L and A_{LL}
- First measurement is consistent with predictions from DSSV

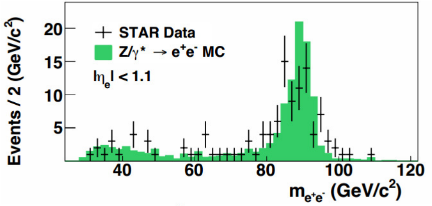


arXiv: 1404.6880

$Z\ A_L$ Result of 2011+2012

$Z \to e^+e^-$ **Candidate**





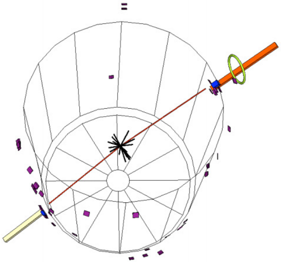
arXiv: 1404.6880

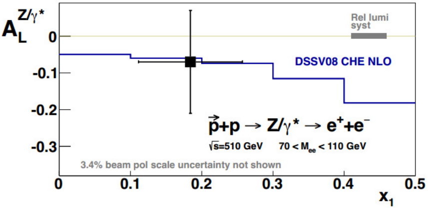
- **Limited Z boson production cross section at RHIC energies.**
- **Fully reconstructed e^+e^- final state.**
- **Reconstruct initial state kinematics at leading order:**

$$x_{1(2)} = \frac{M_{ee}}{\sqrt{s}} e^{\pm yZ}$$

Z A_L Result of 2011+2012

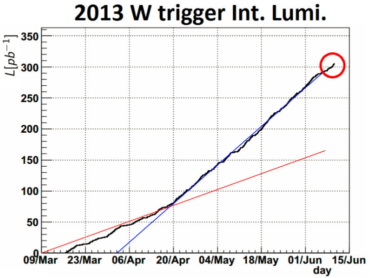
$Z \to e^+e^-$ **Candidate**

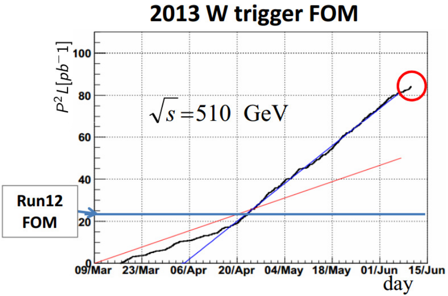




- A_L^Z **is sensitive to the combination of** u,$\bar{u}$,d **and** $\bar{d}$ **polarizations**
- **Consistent with theoretical predictions within the large uncertainty.**

Run 2013 Dataset

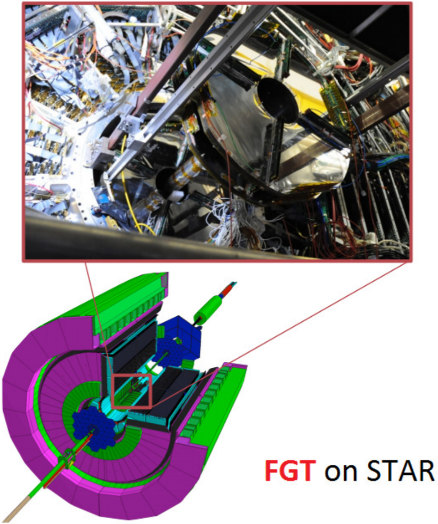




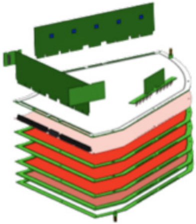
STAR pp500 Longitudinal			
Run	L (pb^{-1})	P	P^2L (pb^{-1})
2009	12	0.38	1.7
2011	9.4	0.49	2.3
2012	77	0.56	24
2013	**∼300**	**∼ 0.53**	**∼84**

- In 2013, STAR collected an integrated luminosity of ∼300 pb^{-1} at $\sqrt{s} = 510$ GeV with an average beam polarization of ∼53%, which is 3 times greater than total of previous years in FOM.

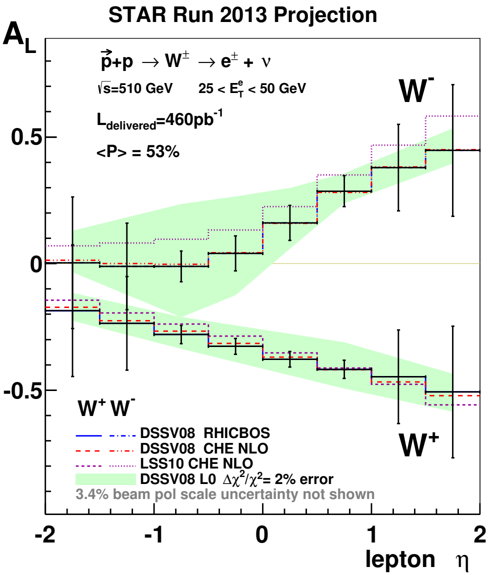
Forward GEM Tracker



- FGT was fully installed for Run 2013
- Acceptance can be enhanced to $\eta < 2$
- FGT analysis is ongoing, will help charge separation



Projection of W A_L for Run 2013



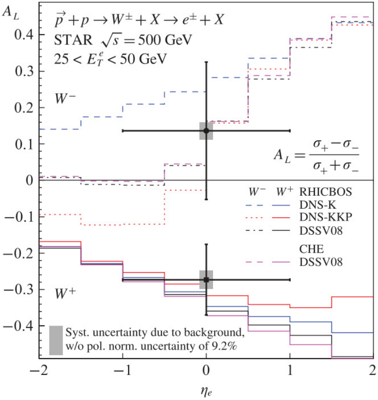
- Extension of backward and forward acceptance enhances sensitivity to $\bar{u}$ and $\bar{d}$ quark polarization
- Higher precision result is expected from much larger statistics of run13 database (being analyzed).

Summary

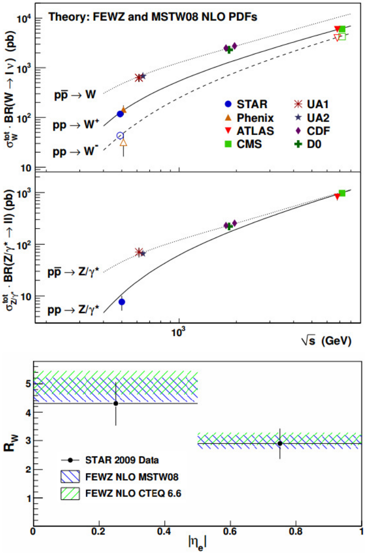
- STAR has measured the parity-violating A_L of W bosons as a function of decayed lepton pseudo-rapidity, η_e, which provides significant constraints on $\Delta\bar{u}$ and $\Delta\bar{d}$
- New constraints on light quark sea polarization from W data, preferring a positive $\Delta\bar{u}$
- A_{LL} of W production and A_L of Z production were also firstly measured, consistent with the theoretical predictions.
- Higher precision data being analyzed now from Run 13

Backup

2009 STAR W Results



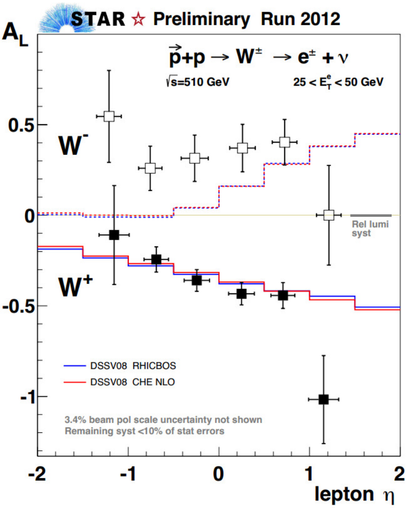
PRL 106, 062002 (2011)

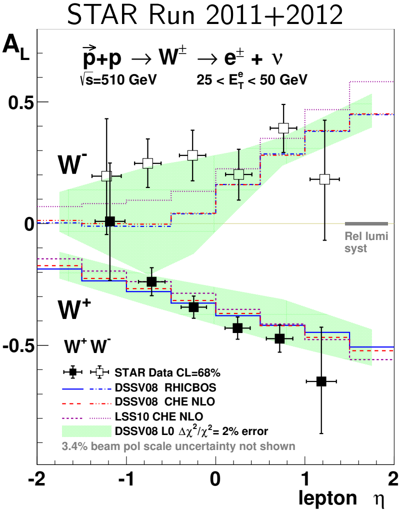


PRD 85, 92010 (2012)

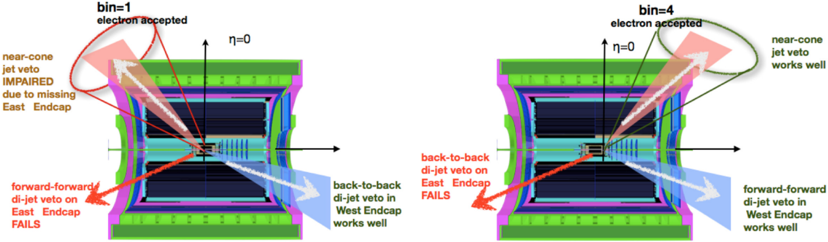
- 2009 was a very successful first 500 GeV physics run

W $A_L(\eta_e)$: 2012 Preliminary Results vs. 2011+2012 Results



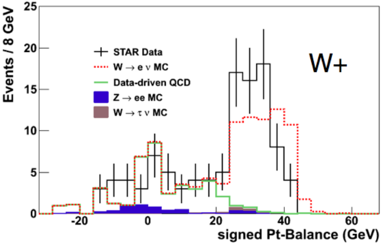


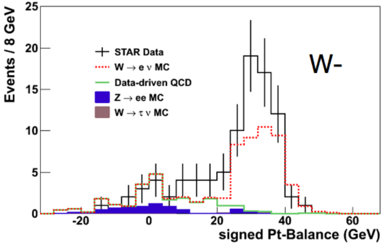
Second EEMC Background



The background events rejected by the **real** EEMC which are measured in the positive detector η bins correspond to the background event that would be removed from the signal yield in the negative detector η bins by a **fictitious** EEMC on the east side of STAR.

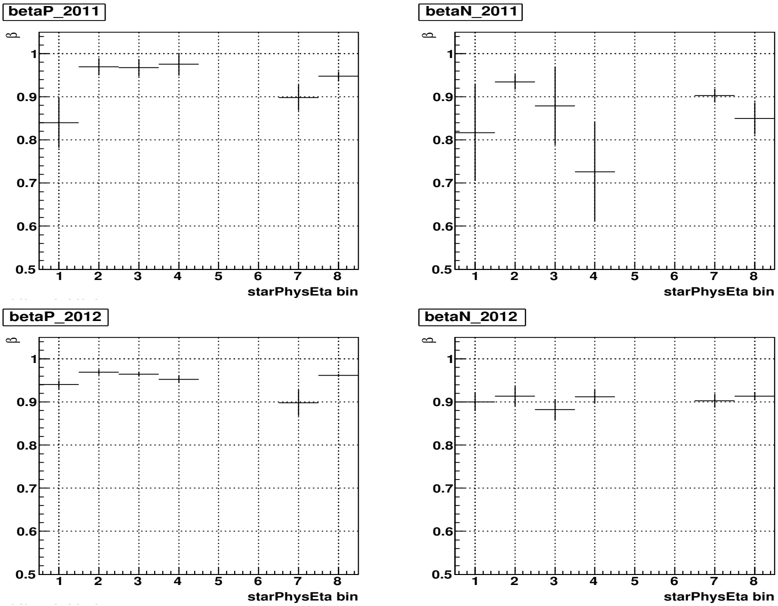
Forward-rapidity Background Estimation





- Similar background estimation to mid-rapidity, but based on P_T-Balance
- Combined 2011 and 2012

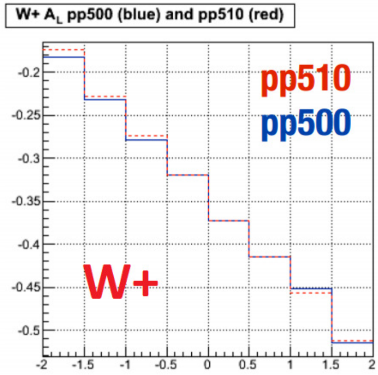
Unpolarized background β

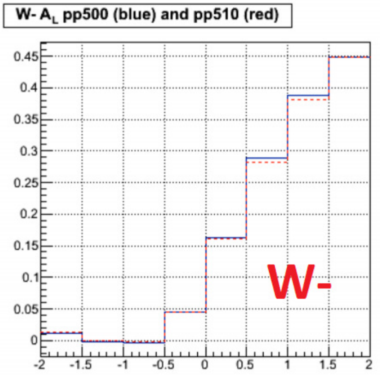


Systematic Uncertainties

- Beam polarization uncertainty: correlated scale 3.4%
- Relative luminosity uncertainty: correlated offset $\Delta A_L = 0.007$
- Background estimation: less than 10% of statistical error

pp $\sqrt{s}$: 500GeV vs 510GeV





- Expect negligible difference in A_L from 2% change in $\sqrt{s}$.
- CHE(NLO) curves with DSSV confirm this expectation